Renewable and Sustainable Energy Reviews 16 (2012) 1089–1098

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Sustainability issues for promotion of Jatropha biodiesel in Indian scenario: A review

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ARTICLE INFO

Article history:
Received 29 December 2010
Accepted 9 November 2011
Available online 6 December 2011

Keywords:
Biodiesel
Jatropha
Sustainability

ABSTRACT

Jatropha, a non-edible oil seed yielding plant has been identified by the Government of India to produce biodiesel under National Biodiesel Mission. Failure of National Biodiesel Mission Phase-I requires critical analysis of all the possible facts related to its long-term sustainability. Present work identifies important sustainability issues related to promotion of Jatropha biodiesel in India. These sustainability issues have been regrouped in four major categories: technological, environmental, economic and social. This paper attempts to explore various sustainability issues taking into account the recent Indian experiences with possible government support/initiatives for successful adoption of Jatropha biodiesel in Indian scenario.

Contents

1. Introduction

Deteriorating global environment, unsustainable energy consumption rate, unequal distribution of resources and resulting social tensions are natural outcomes of an unplanned growth. It has been feared that growing pressure on the environment will outpace the present reform process turning the environment unsustainable. A sustainable system refers to: (a) co-existence of the human species along with other species, (b) maintaining

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doi:10.1016/j.rser.2011.11.014

productivity and elasticity of economic systems, (c) a regenerative and stable environment. India as a developing nation has the responsibility of achieving its development goals with a sustainable socio-economic system. To achieve a sustainable growth, an independent energy system is a pre-requisite. Petroleum products have a critical impact on economics of India due to severe dependency on imports. An integrated approach is required for managing the energy requirement through its efficient use, conservation and promotion of renewable sources [1]. Any search for eco-friendly energy alternatives can be termed as an effort to pay much-needed respect to the environment [2].

The world is confronting with the twin crisis of fossil fuel depletion and environmental degradation. Uses of renewable fuels, energy efficiency and environmental protection have become important issues in recent years. Average sector-wise consumption pattern of petroleum products in India is shown in Fig. 1. Transport sector has clear dominance in overall energy requirements. In 2009–10 diesel consumption was 56.32 MT in India. Projected diesel demand by 2020 may be around 100 MT with 6% annual growth in consumption with an import dependency of 90% of projected demand. These figures suggest an urgent attention on meeting this demand in sustainable manner without affecting the environment. In India diesel consumption stands at almost 40% of total petroleum products consumed at present, hence an alternative fuel needs to be explored for partially meeting the ever increasing demand of diesel. In India, it has been projected that maximum contribution of renewable energy can be around 5–6% by 2031–32 under optimistic scenario. Import dependence on crude oil is expected to be in the range of 90% in next decade making energy security a serious concern for India [4].

Biodiesel feedstock markets worldwide are in a transition from increasingly expensive first generation feedstocks, such as soy, rapeseed, and palm oil to alternative, lower cost, non-food feedstocks [5]. Among various alternatives to petroleum diesel, Jatropha biodiesel looks a promising option for India. *Jatropha curcas* plant is a drought-resistant, perennial plant living up to 50 years and has the capability to grow on marginal soils as it requires very few nutrients to survive. It requires very little irrigation and grows in all types of soils along with arid land where it offers the additional benefit of erosion control thus making Jatropha a more sustainable choice than other vegetable oils [6–9]. There are several other advantages with Jatropha like: shorter gestation period, resistant to common pests, produces non-edible oil, not consumed by the cattle and the byproducts of biodiesel are also quite useful as biofertilizer and glycerin. The seed collection period of Jatropha does not coincide with the rainy season in June–July, when most agricultural activities takes place. This makes it possible for people to generate additional income in the slack agricultural season [10]. Since India has a large wasteland area suitable for Jatropha cultivation, it can supply large volume of biodiesel, provided its cost of production becomes compatible with the price of petroleum diesel.

Government of India tried to ensure 5% blending of petro-diesel with biodiesel by 2007 under National Biodiesel Mission Phase-I. But set target could not be achieved and this failure of National Biodiesel Mission Phase-I requires a critical analysis of all possible causes for ensuring its long-term sustainability.

The present work explores those issues, which require intensive studies to make Jatropha biodiesel a sustainable option.

2. Rationale behind sustainability analysis of Jatropha biodiesel

Phase II of the National Biodiesel Mission of India has the objective of producing sufficient vegetable oil based biodiesel to achieve 20% blending of petro-diesel through accelerating the momentum achieved in the demonstration project during Phase I, converting plantation into a mass movement and consequent geometrical expansion of plantation and other connected activities all over the country. The demonstration project was initiated in 2003 and was scheduled to be completed by 2007 while Phase II was supposed to be started in 2007 and is scheduled to be completed by 2012 [11]. The major reasons cited for taking up this mission are as follows:

- bio-diesel being a superior fuel than petro-diesel from the environmental point of view;
- use of bio-diesel becomes compelling in view of the tightening of automotive vehicle emission standards and court interventions;
- the need to provide energy security, specially for the rural areas;
- the need to create employment;
- providing nutrients to soil, checking soil erosion and land degradation;
- rehabilitating degraded lands through greening;
- addressing global concern relating to containing carbon emissions as provided in the framework convention on climate change; and
- reduce dependence on crude oil imports.

The mission document fails to identify possible threats to this mission. Phase-I of the mission has failed to attract sufficient number of demonstration project and Phase-II has failed to take off. The obvious reasons behind the failure of Phase-I and likely failure of Phase-II are: the inability on identifying critical sustainable issues and possible corrective measures and policy initiatives by the state.

3. Important issues pertaining to sustainability of Jatropha biodiesel in India

Adoption of Jatropha biodiesel or any other biodiesel as a substitute to diesel requires a critical analysis of its sustainability issues. A careful identification of various sustainability issues and establishing their dynamic relationship is a prerequisite for such critical analysis. Following sustainability parameters have been identified and critically analyzed for a sustainable adoption of Jatropha biodiesel in Indian scenario. These sustainability issues can be regrouped in four major categories: technological, environmental, economical and social.

3.1. Technological issues

For successful adoption and promotion of Jatropha biodiesel the most critical issue is its physical and chemical properties as compared to that of petro-diesel so that it can be used straight away in existing engines without any major modifications. Important physio-chemical properties of Jatropha biodiesel as compared to petro-diesel are listed in Table 1.

Table 1
Properties of diesel and Jatropha biodiesel [12].

Property	Diesel	Jatropha biodiesel
Density (kg/m^3)	840 ± 1.732	879
Kinematic viscosity at 40 °C (cSt)	2.44 ± 0.27	4.84
Cetane number	48–56	51–52
Pour point (°C)	6 ± 1	+3
Flash point (°C)	71 ± 3	191
Conradson carbon residue (%, w/w)	0.1 ± 0.0	0.01
Ash content (%, w/w)	0.01 ± 0.0	0.013
Calorific value (MJ/kg)	45.34	38.5
Sulfur (%, w/w)	0.25	<0.001
Carbon (%, w/w)	86.83	77.1
Hydrogen (%, w/w)	12.72	11.81
Oxygen (%, w/w)	1.19	10.97

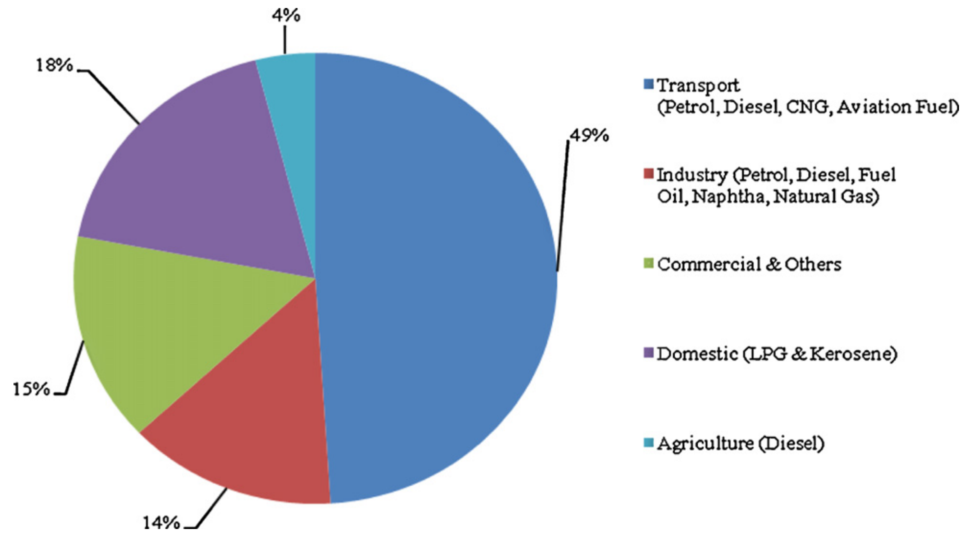

Fig. 1. Average sector-wise consumption pattern of petroleum products in India [3].

Higher Cetane number, very low sulfur content, built in oxygen and higher flash point are some of the properties favoring the utilization of Jatropha biodiesel as fuel in existing diesel engines.

Biodiesel gives considerably lower emissions of particulate matter (PM), carbon monoxide (CO) and hydrocarbon (HC) without any increase in fuel consumption or decrease in engine performance. Biodiesel's particulate reducing effect could be attributed to its lower aromatic and short-chain paraffin HC and higher oxygen content. It has been observed that carbon deposits on the cylinder head, piston top, piston ring grooves, and injector of biodiesel-fueled engine are substantially lower compared to the diesel-fueled engine [13].

For blended diesel with Jatropha biodiesel experimentally it has been observed that a blend of 50% petro-diesel with 50% Jatropha biodiesel (B50) fuel gives performance comparable to that of pure diesel (D100). A blend of 80% petro-diesel with 20% Jatropha biodiesel (B20) gives good mechanical efficiency at full loading conditions [14]. In some studies, higher thermal efficiencies with lower brake specific fuel consumption (BSFC) and higher exhaust temperatures have been reported for all blends of biodiesel compared to mineral diesel [15]. But in some other studies the higher BSFC and lower exhaust temperature have been reported [16]. Technically Jatropha biodiesel possesses the required properties to ensure satisfactory performance of a diesel engine. Certain technological complications require to be addressed to make biodiesel acceptable to automobile industry. Oxidation during storage, poor lubrication properties and problem in cold starting are some of such issues [17]. Basic problem with biodiesel is that it oxidizes while in contact with environment with respect to time which further lead to increase in fuel viscosity [18]. Biodiesel is more prone to oxidation when exposed to higher temperature due to the formation of oxidation products like aldehydes, alcohols, shorter chain carboxylic acids, insolubles, gum and sediment in the biodiesel, which may often be responsible for fuel filter plugging, injector fouling, deposits formation in engine combustion chamber and various components of the fuel system [19]. The oxidation stability of Jatropha biodiesel has been found to increase with increase in dosage of antioxidant. It is found that dosing of 200 ppm of antioxidant is the minimum requirement to meet EN 14112 specification for biodiesel oxidative stability [20].

In a long-term performance evaluation, the engine and fuel system components were disassembled, inspected and evaluated to compare wear characteristics after 4 years of operation and more than 6,00,000 miles accumulation on B20, no difference in wear or other issues were noted during the engine teardown. The cylinder heads of B20 engines contained a heavy amount of sludge around the rocker assemblies that was not found in the diesel engines. The sludge contained high levels of sodium possibly caused by accumulation of soaps in the engine oil. The B20 engines required injector nozzle replacement over the evaluation and teardown period this is due to out of specification fuel. The biological contaminants may be the cause of filter plugging [21].

The cold fuel property of biodiesel requires improvement for large-scale penetration of biodiesel [17,22]. Required hardware modifications may involve all modified injection timing and duration for better combustion of biodiesel in diesel engines [23]. The addition of biodiesel to diesel fuel changes the physico-chemical properties of the blends. With the increase of biodiesel concentration in diesel–biodiesel blends density, kinematic viscosity, cetane number, high heat value, flash and fire point of the blends increase [24].

The brake power and torque of the engine with diesel fuel are higher than those with biodiesel for both naturally aspirated (NA) and turbocharger (TU) operations. Because of higher fuel density and lower heating value, biodiesel shows slightly higher BSFC for both NA and TU operations in comparison with diesel fuel. The use of biodiesel improves the performance and exhaust emissions of the turbocharged engine better compared with the use of diesel fuel [25].

The characteristics of exhaust emissions and particle size distributions of PM from a common rail direct injection (CRDI) diesel engine were investigated with the use of biodiesel and bioethanol blended diesel fuels. The use of biofuel-blended diesel fuels reduced the total number of particles emitted from the engine. However, when compared to the use of D100, the use of biodiesel–diesel blends caused the emission of more particles smaller than 50 nm, which are harmful to human body [26].

In most of the reported studies 20% blend of Jatropha biodiesel with petro-diesel is found to be suitable for normal operations without any modifications in engine specifications. Thus as a technological dimension it would be more appropriate to go for blends rather targeting usage of 100% biodiesel in existing engines or developing engines for operating on biodiesel only.

3.2. Environmental issues

Self-sustainable energy sources will hold the key to prosperity of India in future. India should not look towards a certain group of

countries to meet its ever growing energy needs. It should seriously implement bio-energy development programs as a part of environmental sustainability in the form of clean development mechanism (CDM) [27]. The CDM, established by the Kyoto Protocol, promotes the industrialized nations to provide resources to developing countries in order to support their sustainable development, while at the same time reducing the global green house gases (GHGs) emissions since it is becoming practically impossible to achieve it in their own countries. Biodiesel does not overburden the environment with CO_2 emission as CO_2 from the atmosphere is absorbed by the vegetable oil crop during the photosynthesis process, while the plant is growing. It has already been reported in the literature that biodiesel offers net CO_2 advantage over conventional fuels [28–30]. For realization of high economic growth rate by India, in the coming decades, rapid exploration of the available energy options is called for. Before exploring such energy options it will have to keep in mind its commitment to world community in United Nations Climate Change Conference at Copenhagen, Denmark in December 2009, where it has voluntarily offered to cut its carbon intensity by between 20 and 25% by 2020 from 2005 levels. For achieving such ambitious targets it will require to search for such energy options which offer reduction in GHGs. One such option is the use of Jatropha biodiesel either directly or with its blend with petro-diesel.

The Jatropha plantations projects are entitled for the trade of emission certificates for CO_2 sequestration. One hectare (ha) area can have about 1600 Jatropha plants and each plant has about 200 kg of biomass after five years of life, including roots with dry matter content about 25%. This data gives a dry biomass of 50 kg per plant or 80 tons per hectare plantation. About half of this biomass weight is carbon dioxide, i.e. 25 kg per plant or 40 tons per hectare [31]. Thus, each hectare of Jatropha plantation in fifth year will give 40 CERs under CDM. The trade of certified emission reductions (CERs) pays around US $15.13 per ton of CO_2 sequestration at current market price (as on 20/12/2010 at NCDEX Mumbai, India) which is about US $605 per ha.

In next 10 years the total consumption of petro-diesel is expected to rise by 100% from present consumption level of around 60 MT. This demand cannot be met only through petro-diesel consumption due to supply constraints and its impact on environment. On conservative basis 13.4 MT of petro-diesel can be replaced by Jatropha biodiesel by utilizing available potential waste land of 13.4 Mha.

Comparison of basic combustion equation of petro-diesel with Jatropha biodiesel gives an insight on probable CO_2 emissions reduction.

Ideal combustion equation for petro-diesel ($C_{16}H_{34}$) can be represented as [32]

$$C_{16}H_{34} + 24.5O_2 + 92.12N_2 \rightarrow 16CO_2 + 17H_2O + 92.12N_2 \quad (1)$$

Ideal biodiesel ($C_{18}H_{34}O_2$) combustion equation can be represented as [33]

$$C_{18}H_{34}O_2 + 25.5O_2 + 3.76N_2 \rightarrow 18CO_2 + 17H_2O + 95.88N_2 \quad (2)$$

As shown in Eq. (1), 3.11 kg CO_2 is produced for each kg of diesel fuel used and approximately the same amount of CO_2 would be produced for an equivalent energy content of biodiesel. Available data indicates that Jatropha biodiesel has a calorific value of 38.5 MJ/kg and 45.34 MJ/kg for petro-diesel [12]. Thus, it requires 14.15% more Jatropha biodiesel (mass basis) to produce the same amount of energy as that of petro-diesel, whereas the theoretical carbon balance shows that 11.07% more Jatropha biodiesel will produce the same amount of CO_2. The difference is mainly due to associated oxygen content in the biodiesel. It is among the most critical sustainability parameters for supporting the use of biodiesel. The environmental audits of the entire life cycle of biofuels prove them to be not only carbon-neutral as plants absorb carbon dioxide while growing but also carbon sequestration from 20 to 100%. Fig. 2 shows India is among the top five CO_2 emitting countries of the world. Using biodiesel would definitely lead to reduction in CO_2 emissions.

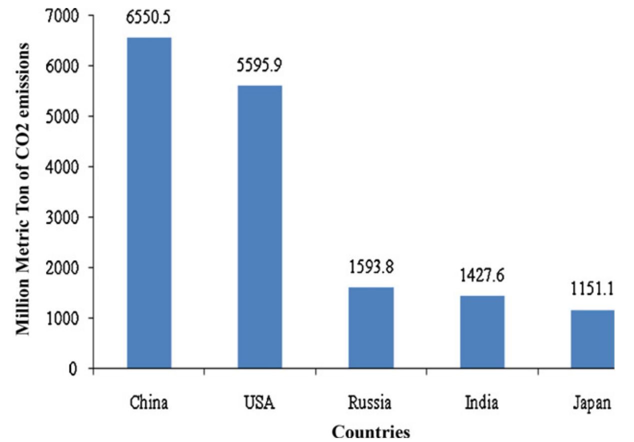

Fig. 2. Major CO_2 emitting countries of the world [30].

As reported, Jatropha plantations can provide alternative viable options to improve the degraded ecosystem improving the fertility of degraded lands. The inclusion of leguminous crops/trees on poor soils can result in marked improvement in soil fertility by: increasing soil organic matter through addition of leaf litter and plant debris, efficient nutrient cycling, efficient biological nitrogen fixation, little loss of nutrients from the system, little erosion run off, additional nutrient economy i.e. uptake from deeper layers and deposition on surface layer via litter [34].

Emissions data of biodiesel compared to diesel in Table 2 reveal that emissions can in fact be reduced by using biodiesel in place of petro-diesel. There is noticeable reduction in CO_2 and SO_2 emissions with the usage of biodiesel in place of diesel.

An integrated approach realizing the benefits of CDM is required to be implemented with proper co-ordination among the various governmental and non-governmental organizations to achieve the targeted production of Jatropha bio-diesel as per National Biodiesel Mission. Such approach assumes more significance for ensuring the welfare of the rural economy while protecting the environment for future generations and for ensuring the availability of green energy at a viable cost.

3.2.1. Emissions from biodiesel blends

Researchers [35–40] have reported that CO, CO_2 and unburnt hydrocarbon (UBHC) emissions are less with bio-diesel and its blends, because bio-diesel has oxygen in its molecular structure leading to better combustion. It has also been reported that NO_x emissions are slightly increased with bio-diesel and its blends with petro-diesel [37,38,40]. This may be due to the higher temperature in the combustion chamber while using biodiesel. The other

Table 2
Bio-diesel emissions compared to conventional diesel [11].

Emissions	B100	B20
Regulated emissions		
Total unburned hydrocarbons	−93%	−30%
Carbon monoxide	−50%	−20%
Particulate matter	−30%	−22%
No_x	+13%	+2%
Non-regulated emissions		
Sulfates	−100%	−20%
Polycyclic aromatic hydrocarbons	−80%	−13%
NPAH (nitrated PAHs)	−90%	−50%
Ozone potential of speciated hydrocarbons	−50%	−10%

most frequently pointed out reason is the use of slightly advanced injection process with biodiesel. NO_x emissions may be reduced by operating engine in dual fuel mode i.e., fuel with high octane number as primary fuel and high cetane number as pilot fuel [37]. Exhaust gas recirculation can result in NO_x emissions reduction up to 50% and reduce smoke emissions by 15% [41,42]. The emission of aromatic and polyaromatic compounds, as well as their toxic and mutagenic effect, has been generally reported to be less with biodiesel. No conclusive trend has been observed regarding the emissions of oxygenated compounds such as aldehydes and ketones [40]. Experimental evidences suggest that overall toxicity of emissions in terms of metals reduces in biodiesel exhaust compared to diesel exhaust [43].

3.3. *Economical issues*

Adoption of any clean fuel technology/biofuel requires a careful consideration on the economical issues such as: production cost, cost–benefit analysis as compared to petro-fuels, long-term availability, possible employment generation, along with other competitive options. Even a serious search for alternative fuel is more dependent on the supply and demand of crude oil and resulting price fluctuations rather than any other issue.

3.3.1. *Demand and supply of crude oil*

The India's energy supply system is dependent on fossil fuels, which are finite looking at their rate of renewability. Growing subsidy bill on petro-products has forced the Government of India to resort to market driven de-regulated petrol pricing depending on international crude prices. 'Oil shock' in 2008 exposed fragile condition of Indian economy burdened with growing fiscal deficit under regulated price regime. This necessitates search for energy options or policies that provides fiscal discipline and decreases the dependence on crude oil imports and saves the foreign exchange reserves for other developmental purposes ensuring energy security with sustainability. Usage of petro-diesel, the largest consumed petro-product in India has shown an average growth of around 4% in past one decade though in the last three years the average growth is around 9%. It clearly indicates that even with conservative estimates in growth of petro-diesel demand by 2020 total petro-diesel demand may be around 100 MT. It would not be economically feasible to meet this demand solely through imports as well as due to supply constraints and its impact on environment.

Availability of crude oil at affordable price in Indian political economic scenario is very important. On account of over dependence on costlier crude oil imports, it is mandatory to have an economically viable alternative. Jatropha biodiesel was being sold at around Rs. 30–32 per liter in India to state run transport corporations for blending purposes [44].

In house crude production in India was 33.51 MT in the year 2008–09 and the diesel consumption was 51.68 MT where as the in house crude production stood at 33.69 MT in the year 2009–10 against the diesel consumption of 56.32 MT [45]. The demand supply gap of petro-diesel is more likely to widen in coming years making Indian economy more vulnerable to international scenario in this sector. A sustainable energy regime requires that dependence on external supply should be at the minimal level. In this regard a policy shift towards the promotion of the use of biodiesel and taking the production level of biodiesel to a sustainable extent requires to be explored.

3.3.2. *Altering fuel demand and use pattern*

Despite a global slowdown in economy, India's energy demand has shown an increasing trend. In terms of end-use, energy demand in the transport sector is expected to be particularly high. Drastic fluctuations have been seen in the pricing of petroleum products.

Table 3
Categorization of waste-land in India [11].

Type of land	Area in Mha
Forest area	3
Boundary plantations	3
Agro forestry	2
Culturable fallow lands	2.4
Waste lands under integrated watershed development	2
Strip land like: railway, road & canal	1
Total	13.4

Worldwide it was argued that biofuels are costing more than the petroleum products. It was only a short-term phenomenon due to a worldwide economic recession causing a fear of decrease in demand. Again the crude price has touched around $80–90 per barrel in October–December 2010. The pricing pattern of any energy product has a direct implication on its demand. The Hubbert's peak oil theory predicts that a peak is nearly reached as far as optimal petroleum production is concerned. It means any further rise in demand of petroleum products would widen the gap between demand and supply leading to further rise in the prices of petro-products.

According to Integrated Energy Policy document published by planning commission India needs to increase its primary energy supply by at least 3–4 times from their 2003–04 levels by 2031–32 in order to maintain 8% growth rate. Future import dependence on crude oil is expected to be in the range of 90% making energy security a concern [4]. Prospect of gas looks good after reported discovery of several gas fields and they may make a significant contribution to India's energy portfolio. Renewable energy options are struggling with low conversion efficiencies, seasonality of supply, problems of storage, high installation cost and high energy cost as compared to conventional energy sources. Integrated Energy Policy formulated by Government of India projects that maximum contribution of renewable energy in an optimistic scenario will be around 5–6% of total energy by 2031–32 [4]. So renewable can be used as a supplement to conventional energy wherever possible. Though in the longer run biofuel as a renewable energy source may not be proven to be a complete substitute for petroleum based products but they can be used along with them in order to reduce dependence on costlier imported petroleum products.

3.3.3. *Affordable land for biofuels*

Issues such as availability of land, without affecting flora, fauna and ecological diversity, become critical for economies like India where food security issues threaten the political and economical stability. There are large tracts of wastelands in India, which have been lying almost barren for decades. From Table 3, it can be observed that around 13.4 Mha of waste land as identified by Indian Government could be utilized for biofuel plantations using wasteland afforestation. Wasteland afforestation is found to be a financially viable and environmentally sound use of most of these lands. In addition, tree planting on wastelands is emerging as a potent tool for arresting the increasing misuse and over-exploitation of these lands and environmental degradation. Although, according to official estimates, available waste land are apparently more than adequate for meeting the targets of Phase-II of National Biodiesel Mission but in reality these lands may not be available for growing Jatropha since these are already occupied or are being used by villagers in some way or other [46].

Most common form of use of the waste land is for cattle husbandry [9]. This would surely be in conflict with Jatropha cultivation as it would remove the only source of livelihood of such section of people which depends on animal husbandry. It would not be easy for the Governments to acquire these lands and

Table 4
Indian land requirement by 2020 in Mha.

Category	Area	References
Food	67	[48]
Commercial & residential space	0.8	[49]
Roads	0.25	[49]

Table 5
Employment generation from Jatropha biodiesel production in man days/hectare [50].

Stage	First year	Second year
Nursery	68	Nil
Plantation	122	29
Post-harvesting	Nil	56
Oil extraction	Nil	15
Trans-esterification	Nil	14
Total	190	114

transfer to the agencies, persons interested in cultivating Jatropha. Taking away lands from them would encounter stiff resistance in many states and thus large-scale farming in the fallow lands particularly by the corporate would not be politically feasible. Under a democratic set up no state can afford to take away land from a large number of farmers through coercion. It may be relevant to mention that in Brazil, the most successful country in ethanol production, where the military government forced a large number of farmers to transfer lands to corporate for cultivating sugarcane that would be used to produce alcohol. State coercion enabled the corporate to acquire and consolidate millions of ha of land at nominal rates [10]. National Action Plan on Climate Change (NAPCC) has a goal of afforestation of 6 Mha of degraded land by 2017 and expanding forest cover from 23% to 33% of India's territory [47].

With growing population several other sectors such as: agriculture, housing, transportation, civic facilities and industry may compete with each other for meeting the other basic needs. Table 4 shows the probable land requirements for different sectors by 2020. This additional requirement may clash with the real availability of potential waste land for Jatropha plantations. The data also shows that major additional land requirement will be for meeting the food requirements. The required area may be lower than this if per hectare yields improve over the years. This also indicates clearly that sparing any cultivable lands for fuels may be very difficult under Indian scenario.

3.3.4. Employment generation

Economic sustainability includes the factors such as lesser dependence on costlier crude oil imports as well as insulating the economy from associated crude oil price fluctuations. One of the major economic benefits that would accrue to a state from the increased use of biodiesel is the presence of a facility that creates energy from locally grown seeds that adds value to the state's industrial and income base. On employability parameters, it can result in manifold increase in employment opportunities. As observed from Table 5, 190 man-days per ha employment is possible in the first year and 114 in the second year.

Thus Jatropha cultivation can be integrated with social schemes of Government of India such as National Rural Employment Guarantee Act (NREGA) for rural poor. The uneven distribution of wealth and with a large population base, India is passing through social unrest in many parts of the country leading to large scale of violence in many forms. Creation of such locally developed employment opportunities for rural poor will also help in diluting social unrest generated due to poverty.

3.3.5. Developing biodiesel supply chain

The marketing and distribution of biodiesel will have to be done in a decentralized manner, owing to the nature of the product through collaboration with a national level body in collaboration with oil marketing companies (OMCs) or through co-operative bodies. A sound marketing and distribution network for biodiesel can ensure the successful adoption of it by the masses. Biodiesel supply chain includes raw material acquisition, storage, processing, storage and distribution as visible from Fig. 3.

An important issue in Indian context is poor availability or non-availability of power has resulted in poor yield or non-optimal utilization of available resources. Co-operative societies/NGOs/Gram Panchayats must ensure crops for biodiesel production in isolated/rural areas. As a matter of policy biofuel crops must be procured on a rational basis by the government designated nodal agency on a viable price. In future this may even lead to severe reduction in pricing of crucial feedstock for the production of biodiesel. Entrepreneurs must be motivated to set up the biodiesel production facility in isolated/remote areas to overcome the energy scarcity and pass on the benefits to true stakeholders for their development. Initially almost every district must have at least one pump station that sells biodiesel. As per the findings, it has been suggested that the websites of oil marketing companies must post a map of retail outlets for biodiesel across the whole country. Moreover, the OMCs, as per the biodiesel purchase policy of Government of India must ensure the regional fuel distributors to get more biodiesel supplied locally as per the quality norms of BIS 15607:2005 at the best possible price [51].

3.3.6. Cost benefit analysis

One of the most important sustainability issues for Jatropha biodiesel is its economics with respect to petroleum-diesel. The cost components of biodiesel are the price of seed, seed collection and oil extraction, oil trans-esterification, transport of seed and oil. At prevailing minimum labour wages of around Rs. 140 per day, the total annual income required will be around Rs. 51,000. With 3.5 tons of Jatropha seed yield per hectare, Rs 16 per kg is minimum advisable price of seeds taking in to care the minimum fertilization and irrigation needs. At Rs 16 per kg of seed cost and considering declared good tax @4% as declared by Government of India, the break even selling price of Jatropha biodiesel comes about Rs. 48 per liter considering gains from selling by-products like seed cake and glycerol as compared to prevailing state administered selling price of petro-diesel around Rs. 41 per liter. 5% blending of biodiesel costing Rs. 48 with petro-diesel of prevailing selling price at approximately Rs. 41 per liter will increase the total cost by around Rs. 0.40 per liter. For 20% blending it will go up by Rs. 1.6 per liter. At prevailing state administered pricing of petro-diesel the OMCs are suffering under recoveries at the rate of Rs. 4.80 per liter corresponding to the prevailing crude pricing in international markets [52].

Looking at the present scenario, a tentative costing of biodiesel has been worked out in Table 6 on the basis of various reported literature [11] and market conditions. From the data, it is evident that cost of Jatropha biodiesel comes out to be around Rs. 48.31 per liter while in the past, biodiesel has been sold at around Rs. 30–32 per liter [44].

Price of petro-diesel is once again hovering around Rs. 41 per liter. Table 7 shows the typical cost components of petro-diesel. Here it can be seen 25% of the cost is local taxation and it forms a large component of revenue for state governments. This aspect has to be taken in to the consideration while forming policy of finalizing the cost of bio-diesel.

Appropriate technology needs to be developed keeping in mind the economies of scale. If the objective is to meet the domestic requirements, small-scale production meeting local requirement

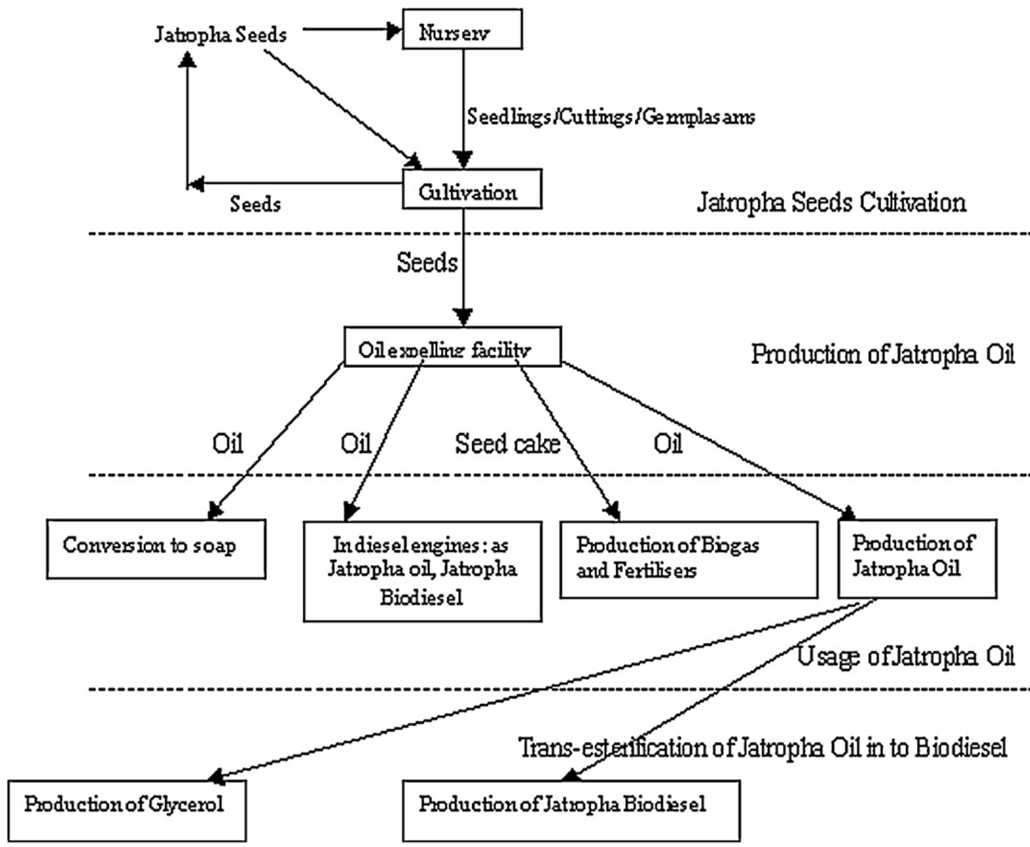

Fig. 3. Jatropha biodiesel supply chain.

Table 6
Cost of biodiesel production.

Cost component	Rate (Rs./kg)	Quantity (kg)	Cost (Rs.)
Seed	16	3.28	52.48
Cost of collection and oil extraction	2.36	1.05	2.478
Less cake produced	1	2.23	−2.23
Trans-esterification cost	6.67	1	6.67
Less cost of glycerol produced	50	0.095	−4.75
Cost of biodiesel per kg			54.65
Declared goods tax@4%			2.19
Total cost per kg			56.84
Cost of biodiesel/liter (specific gravity of 0.85 at 15 °C)			48.31

of biodiesel would not only save a lot of transportation costs but also solve the organizational and coordination problems.

The use of biodiesel is recommended in older engines for reducing emissions, and by providing subsidies equal to the external benefits, cost parity with petro-diesel may be reached. This may result in significant quantity of biodiesel production [53]. Co-operative based production and utilization of Jatropha biodiesel may be more cost effective taking lessons from successful co-operative dairy business model in Indian scenario [54].

Table 7
Retail price of diesel in Bhopal (INDIA) for 1 l as on 01.07.2010.

Heads	Unit	Rate	Total
Ex depot price	Rs/KL	32904.90	32904.90
Reduction	Rs/KL	91.19	−91.19
Entry tax	%	1%	329.05
RPO factor	Rs/KL	21.27	21.27
Local transport	Rs/KL	44	44
Other levies	Rs/KL	1	1
VAT payable	%	23%	7568.13
License fee recovery	Rs/KL	15	15
Retail price	Rs/KL		40792.16
Net retail price	Rs/L		40.79

3.4. Social issues

Indian political system is very sensitive and fragile for any tough economic decision. Acceptability of any new energy source is not only cost sensitive but also seen as a possible threat to revenue earning models of the states on account of high taxation on petro-products. Any adverse publicity of any biofuel for its possible ill effects on soil productivity or cost of food materials may force the state to backtrack from taking any initiatives for promoting the bio-fuels. Under nutrition and hunger are still dominating in rural India resulting in several reported incidents where children have fallen ill after eating up toxic Jatropha seeds causing less social acceptability for Jatropha seeds cultivation.

3.4.1. Food vs fuel

In India about 60% of population is associated with agriculture and related activities and half of this population residing in rural areas is either marginal farmers or landless labourers. Available agricultural land is not proving to be sufficient to grow food grains at an affordable price in India due to lower productivity and dependence on monsoon. Besides this fact, the incentive to switch land use from food crops to fuel crops may severely unbalance food economics if farmers see more profits in biofuel as compared to food crops. Feedstock production for biofuel depends critically on factors like land and water. Future projections of some key socio-economic indicators of India as compared to that of 1990 are shown in Table 8.

These indicators clearly demonstrate the challenges ahead before the Indian economy for meeting the food and energy needs. The competition for land for industrial development, energy

Table 8
Some key socio-economic indicators of India [55].

	1990s	2020s	2050s
Population projections (millions)	846	1354	1888
GDP projections (Rs. Crore)	886,933	5,094,093	14,298,068
Demand for food grains (million tons)	176	295	450
Required food grain productivity (tons/hectare)	1.7	2.3	3.5
Demand for electricity by urban households (mtoe)	3.9	23.4	69.4

plantation and food has picked up in India due to fast growing population. The inability of the industrial and service sectors to generate employment-oriented growth, which can deploy the increasingly young population in the rural areas, has further given rise to migration from rural to urban areas and causing pressure on the urban civic facilities. Traditionally, biomass has been grown as food crops and biomass energy typically is a waste product of agricultural output. In this scenario, there is more synergy than conflict between food and energy security goals. The growing emphasis on the cultivation of bio-fuels may shift the balance of this traditional approach and bio-fuels will start competing for land and water and thus initiating food vs fuel security debate.

Biofuels should not affect yield of main crops threatening food security. Jatropha should be planted into the assigned class of land with poor value crops such as millets and Niger as intercrop. Jatropha can be cropped along with Lentil/Linseed as Rabi crop and along with Mungbean/Cowpea as Kharif crop. It can also be planted in combination with a shaded perennial crop system i.e. Turmeric/ Ginger. It can be cultivated as Agri-Horti-Silviculture with Ber, Brinjal and Mothbean or Karonda, Okra and Clusterbean or Guava and Cucurbits. It can be grown along with medicinal crops like Brahmi, Adusa, Kalmegh, Ashwagandha, Isabgol and Mentha [34].

Furthermore, farmers are not properly sensitized about the cultivation techniques, particularly at the post seedling stage [9]. Farmers assume that once it is planted, it will grow on its own and yield the fruits without any care as it occurs in the wild. In reality it is an input responding plant, meaning that fertile land, fertilizer and pesticides as well as better irrigation will lead to much higher oilseed yields [56]. Therefore, it needs both improvements of the genetic varieties as well as diffusion of cultivation techniques at commercial level.

3.4.2. Toxicity and safety issues

Biodiesel is regarded as non-toxic. The acute oral lethal dose is greater than 17.4 g/kg-body weight. It causes very mild human skin irritation that is less than the irritation produced by 4% soap and water solution. It is biodegradable. Bio-diesel has a flash point of about 300 F well above conventional diesel fuel. The aquatic toxicity of biodiesel has also been found as “insignificant”. Moreover it does not contain chemicals known to cause cancer [11]. It has been reported that the proportion of Jatropha seeds in the diet of mice influences the degree of the pathological abnormality. The inclusion of 5% Jatropha in the diet had no significant effect on liver, heart, kidneys or lungs while inclusion of higher levels of Jatropha produced congestion, haemorrhage and degenerative changes in these organs [57]. It is suggested that the seeds contain large amounts of useful oils and a phytotoxin, similar to ricin of *Ricinus communis* and probably other toxic ingredients [58]. Curcin, a toxalbumin is reported to be highly irritating and remains in the seed after the oil have been expressed [59]. *Jatropha curcas* seeds could be a useful chemotherapeutic agent at a non-lethal dose. In certain African countries people are accustomed to chewing these seeds in form of a laxative. Some researchers have also given examples of natural weeds containing hepatotoxic substances, which may be responsible for liver damage and primary liver tumours in man [60]. Researchers have observed that Preussomerin and deoxypreussomerins molecules of Jatropha plant possess a wide range of biological properties including antibacterial, antifungal, herbicidal, antibiotic and antitumor activities [61,62]. It has also been reported that the *Jatropha curcas* oilcake is not suitable for feeding livestock because of toxic compounds such as phorbol ester and curcin [63–67].

4. Government support/initiatives

Success of any wide spread Jatropha plantation program and promotion of the use of Jatropja biodiesel blends with biodiesel are not possible without active government support and proper policy framework. Huge tax component in the pricing of petro-diesel, as shown in Table 6, makes it very clear that the biodiesel can find its place only after a due support from the government. A fine balance has to be struck where it can be assured that without affecting the state revenue the use of bio-diesel can be promoted. HSD is the largest consumed petro-product in India on account of better mileage, power and lower administered price compared to petrol [68]. Mass utilization of diesel in India imposes a threat to meeting the future energy needs, if the unexpected volatilities in the price of petroleum persists in future and Government of India permits OMCs to sell diesel at uncapped price [69]. The transition from petroleum based oils to other energy sources needs a significant lead time in terms of addressing the technological, economical and environmental aspects and policy issues. Considering vulnerable energy security in India along with the need for sustaining economic development, renewable energy in the form of biofuels is one of the most promising alternatives. Biofuels are the prime candidates aimed at mitigation of climate change impact and waste/barren land reclamation through plantations.

The state has to play a proactive role in motivating and organizing these farmers to cultivate Jatropha. Since the initial few years the poor farmers will not gain anything except spending money and labour, for their immediate survival some alternative sources of earning has to be provided. Not only Brazil, most other countries like the USA, EU countries, etc., are trying to promote biofuel production domestically, adopted various means of providing subsidies, tax concessions, tariff and non-tariff restrictions on imports of biofuels, etc. [9]. Under NREGA, 100 days of wage employment has been guaranteed for the livelihood securities of people in rural areas in a financial year to a rural house hold whose adult members volunteers to do unskilled manual work. Interlinking of this as well as other such type of social welfare schemes for nurturing Jatropha plantations in waste lands and to take care the livelihood needs of cultivators during gestation period till the full growth of Jatropha plant. Favorable biofuel policies may help India in achieving the concept of Energy-based economic development [70]. Issues such as energy security, use of alternative fuels, and interchangeability of technology are vital to ensure that the mix of energy sources used in the economy is optimal and sustainable and that adequate quantities of economically priced clean and green fuels are made available to the Indian consumers [71].

Identification of potential land, providing incentives in form of subsidies and developing a mechanism to support a system during the gestation period along with assuring a minimum support price for Jatropha seeds with a proper collection mechanism are some critical issues required to be answered through government policies. In present scenario targeting 20% blending on uniform basis appears to be more optimistic rather than realistic.

5. Recent Indian experiences with biodiesel

Several state governments like West Bengal, Gujarat, Haryana, Andhra Pradesh, Uttaranchal, Rajasthan and Chhattishgarh have

taken initiatives by setting up nodal agencies to promote cultivation of biodiesel crops primarily Jatropha. Most intensive steps have been taken by Chhattisgarh state government by counter-guaranteeing the purchasing of Jatropha seeds @Rs. 4.50 per kg and biodiesel @Rs. 18 per liter. Government fallow land is being offered on lease to the private entrepreneur to undertake Jatropha plantations. State Government of Andhra Pradesh proposed Jatropha cultivation in 15 lakh acres in next few years with 90% drip subsidy. Jatropha cultivation is to be taken up only in cultivable lands with existing farmers with crop and yield insurance. National Oilseed and Vegetable Oil Development Board (NOVOD) has developed improved Jatropha seeds, which have oil contents up to 1.5 times of ordinary seeds. However, being in short supply, initially these improved Jatropha seeds would be supplied only to Agricultural Universities for multiplication and development.

Indian Railway in general and Southern Railway in particular started using biodiesel as an alternate fuel to petro-diesel. Some private players have also started working in the field of biodiesel on commercial lines. Despite efforts from different agencies no major breakthrough in developing production and distribution system has been achieved in absence of any major initiative at central level [72].

6. Conclusions

Biodiesel holds great promise as a sustainable energy source, if sustainability issues as mentioned above are taken care and analyzed carefully in Indian scenario. These sustainability issues can be regrouped in four major categories: technological, environmental, economic and social.

Important technological issues like higher NO_x emissions, oxidation during storage, poor lubrication properties and problem in cold starting also need to be addressed to make the use of biodiesel acceptable to industry. Issues such as green house effect, potential of mitigating environmental degradation, and impact on soil are part of environmental issues. Using biodiesel would definitely lead to reduction in CO_2 emission. Jatropha plantation can provide alternative viable options to improve the degraded ecosystem improving the fertility of degraded lands. Pricing issue, impact of by products on the production economics, potential of earning carbon credits are few issues related to economic sustainability of bio-diesel. Employment generation, debate on energy vs food, government policies are part of social issues.

Interlinking of state sponsored social welfare schemes for providing livelihood with works such as: nurturing Jatropha plantations in waste lands and for meeting the livelihood needs of cultivators during gestation period till the full growth of Jatropha plant require a careful policy draft on the part of government. Availability of land, for Jatropha plantation on commercial basis, is a major constraint. By 2020 for meeting the food needs only, additional 67 Mha land may be required. Thus leaving anything for meeting the biofuel needs from cultivable lands is almost impossible under Indian scenario. On employability parameters, it can result in manifold increase in employment generation for rural people under NREGA. Thus biodiesel development by itself could become a major poverty alleviation programme for the rural poor apart from providing energy security to the country in general and to the rural areas in particular and upgrading the rural non-farming sector.

Recent Indian experience make it necessary to set up demonstration units in different parts of the country in order to further analyze the yield, and effectiveness of the cultivation techniques in the field under different locations, and to acquaint the neighboring cultivators with the crops, cultivation techniques, productivity and economic benefits, and thus to motivating the cultivators to grow this crop. A focus on one issue may not necessary yield positive impact on another issue. Thus a fine balance has to be struck in all the relevant sustainability issues yielding an optimal solution while framing any policy framework or government initiative to promote the large-scale production and use of bio-diesel. Co-operative based production and utilization of Jatropha biodiesel may be more cost effective taking lessons from successful co-operative dairy business model in Indian scenario.

In India research on bio-diesel is in infant stage, failure of Phase-I of National Biodiesel Mission has also raised serious queries about the preparedness of India to develop and use biodiesel. There is a dire need to adopt rigorous programs on the technological development for its production, utilization of by products and evaluation in various types of engine with respect to power output, emissions and even malfunctioning, etc.

Acknowledgement

Authors are thankful to the School of Energy and Environment Management of R.G.P.V. Bhopal, M.P., India, for all the support provided during this work.

References

[1] Editorial Energy and its sustainable development for India. Energy 2009;34:923–7.
[2] World Commission on environment and development. Our common future. Oxford University Press; 1987.
[3] Goel AK. Petroleum Conservation Research Association (PCRA) India. Available at: http://www.petrofed.winwinhosting.net/upload/5June08/./AKGoel_PCRA.ppt.
[4] Planning Commission Report of the Expert Committee on Integrated Energy policy. Government of India; 2006. Available at: http://www.planningcommission.nic.in/reports/genrep/rep_intengy.pdf.
[5] Markevicius A, Katinas V, Perednis E, Tamasauskiene M. Trends and sustainability criteria of the production and use of liquid biofuels. Renewable and Sustainable Energy Reviews 2010;14:3226–31.
[6] Reubens B, Achten WMJ, Maes WH, Danjon F, Aerts R, Poesen J. More than biofuel? Jatropha curcas root system symmetry and potential for soil erosion control. Journal of Arid Environments 2011;75(2):201–5.
[7] NOVOD. Jatropha: an alternate source of biodiesel. New Delhi, 2007. Available at: http://www. novodboard.com/Jatropha-english.pdf.
[8] NOVOD. Cost of plantation of TBOs. New Delhi, 2008. Available at: http://www.novodboard.com/3rd%20R&D-Report.pdf.
[9] Altenburg T, Dietz H, Hahl M, Nikolidakis N, Rosendahl C, Seelige K. Biodiesel in India value chain organisation and policy options for rural development. Bonn: German Development Institute; 2009.
[10] Biswas PK, Pohit S, Kumar R. Biodiesel from Jatropha: can India meet the 20% blending target? Energy Policy 2010;38(3):1477–84.
[11] Planning Commission Report of the Committee on Development of Biofuel. Government of India, 2003.
[12] Kumar S, Chaube A, Jain SK. Critical review of performance of CI engines using Jatropha Biodiesel and diesel blends based on the observed physical and chemical properties. In: Proceedings of International Conference on Issues and Challenges in Energy Conversion and Management organized by RGPV Bhopal (M.P.) and ISME India, 18–20 March. 2008. p. 365–72.
[13] Kelvin S, Gerpan J. The effect of biodiesel fuel composition on diesel combustion and emission. SAE 1996, doi:10.4271/961086.
[14] Kumar S, Chaube A, Jain SK. Performance characteristics of a single-cylinder four-stroke diesel engine operating with Jatropha biodiesel blended with diesel. Asian Journal of Experimental Sciences 2010;24:111–9.
[15] Agarwal AK. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Progress in Energy and Combustion Science 2007;33:233–71.
[16] Canakci M. Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel. Bioresource Technology 2007;98:1167–75.
[17] Carraretto C, Macor A, Mirandol A, Stoppato A, Tonon S. Biodiesel as alternative fuel: experimental analysis and energetic evaluations. Energy 2004;29:2195–211.
[18] Jain S, Sharma MP. Prospects of biodiesel from Jatropha in India: a review. Renewable and Sustainable Energy Reviews 2010;14:763–71.
[19] Jain S, Sharma MP. Thermal stability of biodiesel and its blends: a review. Renewable and Sustainable Energy Reviews 2011;15:438–48.
[20] Sarin R, Sharma M, Sinharay S, Malhotra RK. Jatropha–Palm biodiesel blends: an optimum mix for Asia. Fuel 2007;86:1365–71.

[21] Murugesan A, Umarani C, Subramanian R, Nedunchezhian N. Bio-diesel as an alternative fuel for diesel engines – A review. Renewable and Sustainable Energy Reviews 2009;13(3):653–62.
[22] Szulczyk KR, McCarl BA. Market penetration of biodiesel. Renewable and Sustainable Energy Reviews 2010;14:2426–33.
[23] Sahoo PK, Das LM. Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine. Fuel 2009;88:994–9.
[24] Sahoo PK, Das LM, Babu MKG, Arora P, Singh VP, Kumar NR. Comparative evaluation of performance and emission characteristics of Jatropha, Karanja and Polanga based biodiesel as fuel in a tractor engine. Fuel 2009;88(9):1698–707.
[25] Karabektas M. The effects of turbocharger on the performance and exhaust emissions of a diesel engine fuelled with biodiesel. Renewable Energy 2009;34:989–93.
[26] Kim H, Choi B. The effect of biodiesel and bioethanol blended diesel fuel on nanoparticles and exhaust emissions from CRDI diesel engine. Renewable Energy 2010;35:157–63.
[27] Kumar S, Chaube A, Jain SK. Issues pertaining to substitution of diesel by Jatropha biodiesel in India. Journal of Environmental Research and Development 2010;4(3):877–84.
[28] Alcantara R, Amores J, Canoira L, Fidalgo E, Franco MJ, Navarro A. Catalytic production of biodiesel from soy-bean oil, used frying oil and tallow. Biomass Bioenergy 2000;18:515–27.
[29] Antolin G, Tinaut FV, Briceno Y, Castano V, Perez C, Ramirez AI. Optimisation of biodiesel production by sunflower oil transesterification. Bioresource Technology 2002;83:111–4.
[30] International Energy Agency (IEA). Co_2 emissions from fuel combustion Highlights Paris, France, 2010 Edition. Available at: http://www.iea.org/co2highlights/co2highlights.pdf.
[31] Hooda N, Rawat VRS. Role of bio-energy plantations for carbon-di-oxide mitigation with special reference to India. Mitigation and Adoption Strategies for Global Change 2006;11:445–67.
[32] Peterson CL, Hustrulid T. Carbon cycle for rapeseed oil biodiesel fuels. Biomass and Bioenergy 1998;14(2):91–101.
[33] Rajesh S, Raghavan V, Shet USP, Sundararajan T. Analysis of quasi-steady combustion of Jatropha bio-diesel. International Communications in Heat and Mass Transfer 2008;35:1079–83.
[34] Gour VK. Production practices including post harvest management of *Jatropha curcas*. In: Biodiesel Conference towards Energy Independence – Focus on Jatropha. 2006.
[35] Barnwal BK, Sharma MP. Prospects of bio diesel production from vegetable oils in India. Renewable and Sustainable Energy Reviews 2005;9:363–78.
[36] Vellguth G. Performance of vegetable oil and their monoesters as fuels for diesel engines. SAE 1983, doi:10.4271/831358.
[37] Senthilkumar M, Remesh A, Nagalingam B. Complete vegetable oil fueled dual fuel compression ignition engine. SAE 2001;2001:28–0067.
[38] Kegl B. Effects of biodiesel on emissions of a bus diesel engine. Bioresource Technology 2008;99:863–73.
[39] Raheman H, Phadatare AG. Diesel engine emission and performance from blends of Karanja methyl ester and diesel. Biomass Bioenergy 2004;27:393–7.
[40] Lapuerta M, Armas O, Fernandez JR. Effect of biodiesel fuels on diesel engine emissions. Progress in Energy and Combustion Science 2008;34(2):198–223.
[41] Greeves G, Wang CHT. Origins of diesel particulate mass emission. SAE 1981, doi:10.4271/810260.
[42] Nabi MN, Akhter MS, Shahdat MZ. Improvement of engine emissions with conventional diesel fuel and diesel bio diesel blends. Biosource Technology 2006;91:372–8.
[43] Dwivedi D, Agarwal AK, Sharma M. Particulate emission characterization of a biodiesel vs diesel-fuelled compression ignition transport engine: a comparative study. Atmospheric Environment 2006;40:5586–95.
[44] Paul A. Government restriction on sale of biodiesel disrupts production, Posted: Thursday, June 11 2009. 12:49 AM IST, http://www.livemint.com/2009/06/11003630/Government-restriction-on-sale.html (accessed 26.12.10).
[45] Basic Statistics on Indian Petroleum & Natural Gas 2009–10. Ministry of Petroleum & Natural Gas Government of India New Delhi (Economic Division). Available at: http://petroleum.nic.in/petstat.pdf.
[46] The Energy and Resources Institute (TERI). Liquid biofuels for transportation: India country study on potential and implications for sustainable agriculture and energy. New Delhi, 2005.
[47] Ghosh P. National Action Plan on Climate Change, Prime Minister's Council on Climate Change, October 2009. Available at: http://moef.nic.in/downloads/others/CC_ghosh.pdf.
[48] Sharma N. Population and economic growth as drivers of future land use in India. Environment & Policy 2006, doi:10.1007/1-4020-4368-6.
[49] Sankhe S. et al. India's urban awakening: building inclusive cities, sustaining economic growth. Mckinsey Global Institute, April 2010. Available at: http://www.mckinsey.com/mgi/reports/freepass_pdfs/india_urbanization/MGI_india_urbanization_fullreport.pdf.
[50] Adholeya A, Dadhich PK. Production and technology of bio-diesel: seeding a change. New Delhi, India: The Energy and Resources Institute (TERI); 2008.
[51] Ministry of Petroleum and Natural Gas. Bio-diesel Purchase Policy. Government of India, 2005.
[52] The Economic Times. Diesel price hike decision on Dec 22. 14th December 2010. New Delhi, India.
[53] Charles S, Wassell Jr, Timothy P, Dittmer. Are subsidies for biodiesel economically efficient? Energy Policy 2006;34:3993–4001.
[54] Kumar S, Chaube A, Jain SK. Economic sustainability of Jatropha biodiesel in India. Journal of Environmental Research and Development 2008;03(01):292–300.
[55] Socio-economic scenarios for climate change impacts in India. Keysheet 3. The Energy and Resources Institute (TERI), India. Available at: https://www.decc.gov.uk/assets/decc/what%20we%20do/global%20climate%20change%20and%20energy/tackling%20climate%20change/intl_strategy/dev_countries/india/india-climate-3-socio-econ.pdf.
[56] Jongschaap REE, Corre WJ, Bindraban PS, Brandenburg EA. Claims and facts on *Jatropha curcas* L. Global *Jatropha curcas* evaluation, breeding and propagation programme. Report 158. Wageningen: Plant Research International B.V.; 2007.
[57] Adam SEI. Toxic effects of *Jatropha curcas* in Mice. Toxicology 1974;2:67–76.
[58] Kingsbury JM. Poisonous Plants of the United States and Canada. Englewood Cliffs, NJ: Prentice-Hall; 1964, 191.
[59] Watt JM, Breyer-Brandwijk NG. Medicinal and poisonous plants of Southern and Eastern Africa. 2nd ed. Edinburgh: Livingstone; 1962, 422.
[60] Schoental R. Liver disease and natural hepatotoxins. Bulletin of the World Health Organization 1963;29:823.
[61] Ravindranath N, Reddy MR, Mahender G, Ramu R, Kumar KR, Das B. Deoxypreussomerins from *Jatropha curcas*: are they also plant metabolites? Phytochemistry 2004;65(16):2387–90.
[62] Wipf P, Jung JK, Rodriguez S, Lazo JS. Synthesis and biological evaluation of deoxypreussomerin A and palmarumycin CP1 and related naphthoquinone spiroketals. Tetrahedron 2001;57:283–96.
[63] Joubert PH, Brown JM, Hay IT, Sebata PD. Acute poisoning with *Jatropha curcas* (purging nut tree) in children. South African Medical Journal 1984;65: 729–30.
[64] Abdu-Aguye I, Sannusi A, Alafiya-Tayo RA, Bhusnurmath SR. Acute toxicity studies with *Jatropha curcas* L. Human Toxicology 1986;5(4): 269–74.
[65] Levin Y, Sherer Y, Bibi H, Schlesinger M, Hay E. Rare *Jatropha multifida* intoxication in two children. Journal of Emergency Medicine 2000;19(2): 173–5.
[66] Kulkarni ML, Sreekar H, Keshavamurthy KS, Shenoy N. Jatropha curcas – poisoning. Indian Journal of Pediatrics 2005;72(1):75–6.
[67] Menezes RG, Rao NG, Karanth SS, Kamath A, Manipady S, Pillay VV. *Jatropha curcas* poisoning. Indian Journal of Pediatrics 2006;73(7):634.
[68] Kumar S, Chaube A, Jain SK, Jatropha. Biodiesel a promising C.I Engine alternate fuel in India. Indian Journal of Applied Life Sciences 2008;4(1&2): 1–5.
[69] Kumar S, Chaube A, Jain SK. Jatropha biodiesel: a prominent renewable biofuel in India. Indian Journal of Applied Life Sciences 2008;4(1&2):14–9.
[70] Carley S, Lawrence S, Brown A, Nourafshan A, Benami L. Energy-based economic development. Renewable and Sustainable Energy Reviews 2011;15: 282–95.
[71] Pode R. Addressing India's energy security and options for decreasing energy dependency. Renewable and Sustainable Energy Reviews 2010;14: 3014–22.
[72] Petroleum Conservation and Research Association India. <http://www.pcra-biofuels.org>.